Linear Regression Model of the Conveyor Type Transport System

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Abstract. This article discusses the prospects of using linear regression models to describe multi-section branched transport systems of conveyor type. A characteristic feature of the functioning of a multi-section transport system is the presence of resonant peak values for the flow parameters of the transport system and transport delay. Various variants of the linear regression model are investigated. It is shown that for multisection transport systems with a periodic nature of the magnitude of the incoming material flow into the transport system and periodic nature of the regulation of the belt speed the value of the transport delay is a quasi-stationary value. The transport delay can be excluded from model variables. Analysis of the various variants of linear regression models considered in the article shows that using them to describe branched transport systems is ineffective. The considered models can only be used for a qualitative analysis of the output stream from the transport system. The absence of a linear relationship between the input and output flow parameters of the transport system is shown.

Keywords: conveyor, PDE-model, distributed system, linear regression model.

Introduction

The conveyor belt is an important element between the place of material extraction and the place of material processing. Increasing the throughput of the transport system and increasing its length leads to an increase in the cost of transporting material by the conveyor system. The cost of transporting material is more than 20% of the total cost of material mining [1]. With an increase in the length of the transport route, transportation costs increase. For long main conveyors [2, 3], the increase in transportation costs can be significant due to the unevenness of the incoming material flow, and, as a consequence, its uneven distribution along the transport route. For transport systems not loaded up to the nominal value, the share of transport costs in the total production cost becomes much higher than the normative. One of the effective ways to reduce transport costs is to increase a load of material on the transport conveyor [4]. This is achieved by belt speed control [5, 6] or the material flow control at the input of a separate conveyor section. To control the flow of material at the input to the conveyor section, an accumulate bunker is usually installed [7.8]. Optimal flow parameters control of the transport system makes it possible to provide the best option for filling the transport route with the material, which leads to lower transportation costs. To construct an algorithm for optimal parameters control by a separate conveyor section, a sufficient number of conveyor models have been developed [9, 10]. From all of them, two types of models attract attention. The first type of model is based on the use of the finite element method [11, 12]. This type of model makes it possible to obtain a numerical solution that determines the state of the section parameters. The analytical type PiKh–model belongs to the second type [13, 14]. These two types of models make it possible to obtain a description of the conveyor section with a given accuracy.

1 Formal problem statement

An increase in the length of the transport system leads to a separation of the transport route into individual sections. The development of new mines lead to the emergence of new routes for the transportation of materials, increases the branching of the transport system. The presence of such a trend complicates the use of the considered two types of models for constructing algorithms for optimal control of the flow parameters of a branched multi-section transport conveyor. The complexity of the description lies both in increasing the number of equations depending on the number of sections, and in increasing the number of interrelations between the parameters of the transport system.

The perspectives for their use are limited by the number of sections. It should be assumed that the first class of models should be used to describe transport systems with the number of sections not exceeding ten.

The use of the second class of models is limited by the number of sections not exceeding one hundred sections. However, at present, transport systems already consist of several dozen sections [8.15]. This fact makes it relevant to use regression models, and also models based on a neural network, to describe a multi-sectional transport system.

The number of input parameters in such a description, as a rule, is determined by the number of sections through which material flow incomes the transport system directly from the mine.

The number of input sections can be significantly less than the number of internal sections, which significantly reduces the number of variables for describing the transport system. For example, the main conveyor from the Bu Craa mine to the coast at El Aaiún, Western Sahara [16] consists of eleven sections, among which there is only one input section. These circumstances increase interest in using regression models and models that are based on a neural network to describe a transport system. In this paper, we will focus on the use of the linear regression equation for modelling complex transport systems.

2 Literature review

In paper [17], a linear regression model was considered to predict the optimal service life of a conveyor belt. To build a regression model, eighteen conveyors were studied. The following parameters were used as model parameters: width, thickness, length of the conveyor belt S_d, belt speed $a(t)$ and cargo flow of material $[\chi]_1(t,S)$, which passes through the section of the conveyor. The linear regression equation for predicting the speed of wear of the belt of the conveyor section depending on the conveyor belt speed $a(t)$ and the cargo flow of the material $[\chi]_1(t,S)$ is given in [18]. In [19], a linear regression model is considered to analyze the effect of shock load on a conveyor belt by incoming material. The aim of the experiment is to determine the dependence of impact force F_I, respectively tension force F_S from independent variables: the weight of the ram (m) and the amount of impact ram (h). A regression model for the prediction of idler rotational resistance on a belt conveyor is shown in [20]. Multiple regression is used to find the relationship between the two main independent variables, as the volume of transported material, the angle of the conveyor, and the dependent variable SEC (special energy consumption), [21]. The presented review shows that the linear regression equation can be successfully used to solve two types of problems. The first type of problem is predicting the degree of wear of the components of the conveyor section depending on the magnitude of the conveyor section flow parameters. The second type of the problem is to determine the effect of the flow parameters of a separate section on the specific energy consumption that is spent on transporting one ton of material over a distance of one meter (SEC), [21]. The most commonly used as regressors are the flow parameters as the belt speed $a(t)$ and the cargo flow of material $[\chi]_1(t,S)$, which passes through the conveyor section. In this paper, we will expand the area of application of the linear regression model for transport systems which consist of a large number of sections and consider the possibility of their use for predicting the dependencies between the input and output transport system flow parameters.

3 The main parameters of the conveyor model

The structural diagram of a multi-section transport conveyor is given in [8, 15]. Let us consider the construction of the linear regression equation and the analysis of the prediction results on the example of eight sectional transport conveyors (Fig. 1). The proposed method can be used to build a linear regression model for a transport system with an arbitrary number of sections.

To describe the state of the transport system, let us introduce dimensionless variables

$$\tau = \frac{t}{T_d}, \ \xi = \frac{S}{S_d}, \ \xi_d = \frac{S_{dm}}{S_d} \tag{1}$$

$$\theta_{0\mathrm{m}}(\tau,\xi)=\frac{[\chi]_{0\mathrm{m}}(t,S)}{\Theta},\ \psi_m(\xi)=\frac{\Psi_m(S)}{\Theta},\ \gamma_m(\tau)=\lambda_m(t)\frac{T_d}{S_d\Theta}, \tag{2}$$

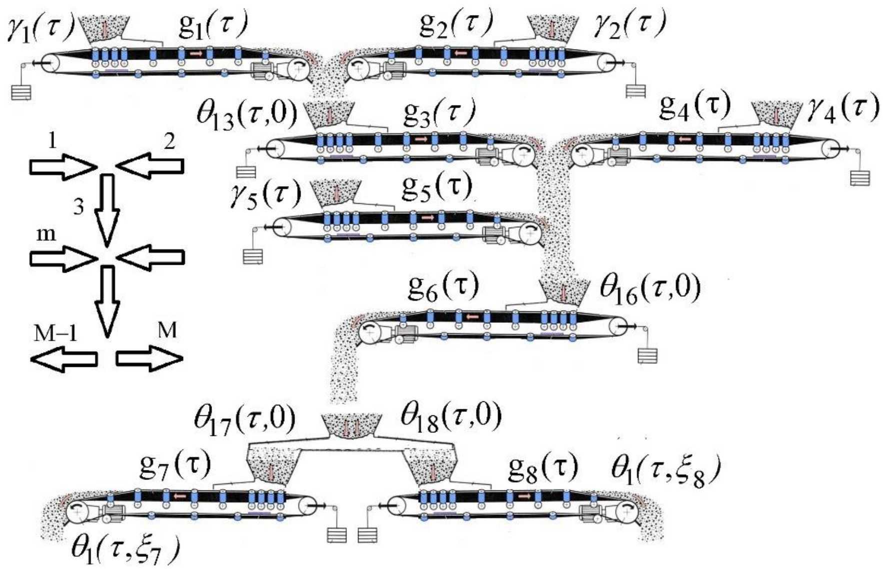

Fig. 1. Diagram of a branched conveyor transport route

$$g_m(\tau)=a_m(t)\frac{T_d}{S_d},\ \Theta=\max\left\{\Psi_m(S),\frac{\lambda_m(t)}{a_m(t)}\right\}, \tag{3}$$

where parameters $[\chi]_{0m}(t,S)$ (t/m), $[\chi]_{1m}(t,S)$ (t/h) are the linear density of the rock and the rock flow along the transport route of the m-ой section at time t (h) at the point of the transport route with coordinate S (m); $a_m(t)$ (m/h) is the belt speed of the m-th section; λ_m(t) is the intensity of rock incoming at the input of the m-th conveyor section at a point with coordinate S=0; $\Psi_m(S)$ (t/m) is initial distribution of material along the m-th section length S_{dm}; S_d is the characteristic length of the conveyor section; T_d is the characteristic time over which the material passes the transportation route length S_d. The intensity of material λ_m(t) incoming to the input of the m-th section of the conveyor is set exclusively for the input sections, through which the material from the mine enters the transport system. Such sections in the transport system of Fig. 1 should be considered sections m = 1,2,4,5. For the other sections, the intensity of the material flow λ_m(t) is determined by the value of the material flow incoming from the previous section. During the operation of the conveyor section, the material flow λ_m(t) and the belt speed $a_m(t)$ change in the range limited by the maximum and minimum values and are periodic in nature [22]. Thus,

$\lambda_m(t)$ and $a_m(t)$ can also be represented as an expansion in periodic functions. Let's limit ourselves to the first harmonics of decomposition, write the dimensionless intensity of the material, the speed and initial distribution in the form:

$$\gamma_m(\tau) = \gamma_{0\,m} + \gamma_{0\,m} \sin\left(m\pi\tau - \frac{m\pi}{4}\right), \tag{4}$$

$$g_m(\tau) = g_{0\,m} + \frac{g_{0\,m}}{2} \sin\left(m\pi\tau + \frac{m\pi}{3}\right), \tag{5}$$

$$\psi_m(\xi) = \psi_{0\,m} + \psi_{0\,m} \sin\left(m\pi\xi + \frac{m\pi}{4}\right). \tag{6}$$

where

$$g_{0\,m} = \frac{3+m}{8},\ \gamma_{0\,m} = \frac{3+m}{24},\ \psi_{0\,m} = \frac{3+m}{24}. \tag{7}$$

The view of functions $\gamma_m(\tau)$ и $g_m(\tau)$ for the input sections m = 1,2,4,5 for the time interval $0 \le \tau \le 2$ is shown in Fig. 2, Fig. 3.

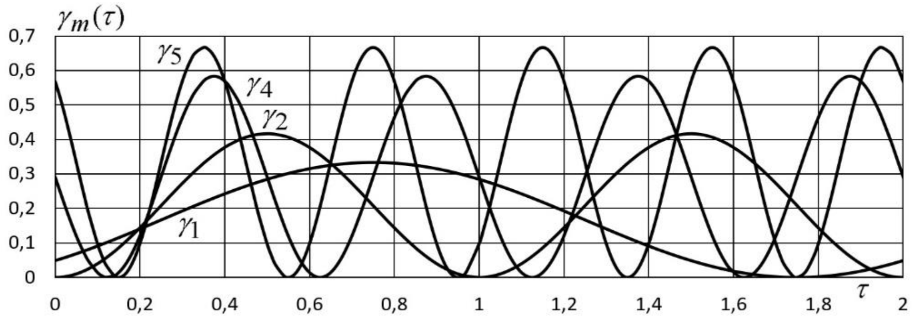

Fig. 2. The intensity of the flow material $\gamma_m(\tau)$ at the input of the m-th section

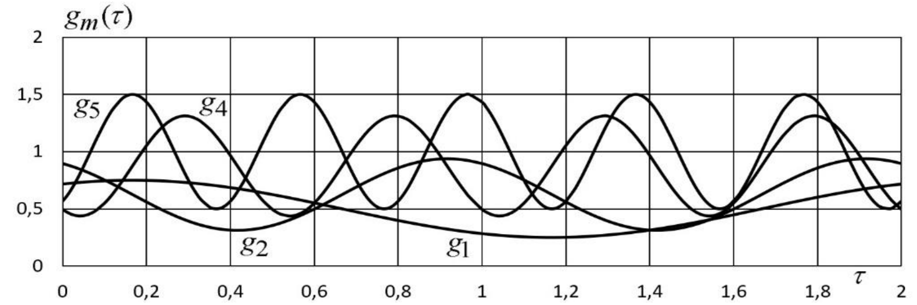

Fig. 3. The belt speed $g_m(\tau)$ of the m-th section

The system of equations (4)–(7) forms the output flow $\theta_1 = \theta_1(\tau, \xi_m)$ of the transport system. The distribution density $f(\theta_1)$ for the output flow θ_{17}, θ_{18} sections m = 7.8 of the transport system (Fig. 2) is shown in Fig. 4. The tail of the distribution density has characteristic local maximums associated with the periodic law of the input parameters of the transport system (4) - (7). The statistical characteristics of the cargo flow of material at the input of the transport system are analyzed in [22, 23]. Studies in [24, 25] indicate that the minute flow at the input to a separate section has a distribution law close to the normal distribution law. The material flow of the output sections (Fig. 4) was calculated based on the analytical PiKh–model [13]. The value of the flow parameters at the output of a separate section can be determined by the equations (8)–(10):

$$\theta_{0\mathrm{m}}(\tau,1) = \left(1 - H\left(1 - G(\tau)\right)\right)\frac{\gamma_m(\tau - \Delta\tau_{\xi_m})}{g_m(\tau - \Delta\tau_{\xi_m})} + \mathrm{H}(1 - G_m(\tau))\psi_m(1 - G_m(\tau)) \tag{8}$$

$$\theta_{1\mathrm{m}}(\tau,1) = g_m(\tau)\theta_{0\mathrm{m}}(\tau,1),\ G_m(\tau) = \int_0^{\tau} g_m(\omega)d\omega\ ,. \tag{9}$$

$$G_m^{-1}(G_m(\tau) - \xi_m) = \tau - \Delta\tau_{\xi_m},\ G_m^{-1}(G_m(\tau)) = \tau\ . \tag{10}$$

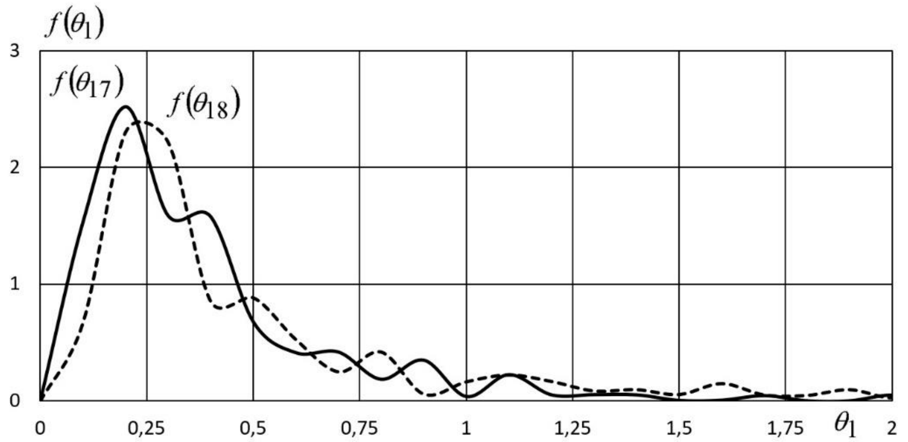

Fig. 4. The distribution density $f(\theta_1)$ of the output flow of material $\theta_{1\mathrm{m}}(\tau,1)$

From the calculation of the transport delay $\Delta\tau_{\xi_m}$ (10) it should be assumed that the transport delay has a value close to a constant value (Fig. 5). This makes it possible to assume that the transport delay value determined by conditions (5), (7) does not significantly affect the value of the output flow of the transport system.

This fact confirms the values of the correlation coefficient $r_{\Delta\tau_m\theta_{18}}$ between the transport delay $\Delta\tau_{\xi_m}$ and the output material flow $\theta_{18}(\tau,1)$: $r_{\Delta\tau_1\theta_{18}} = 0$, $r_{\Delta\tau_2\theta_{18}} = -0.09$, $r_{\Delta\tau_3\theta_{18}} = -0.08$, $r_{\Delta\tau_4\theta_{18}} = -0.01$, $r_{\Delta\tau_5\theta_{18}} = 0.01$, $r_{\Delta\tau_6\theta_{18}} = -0.15$.

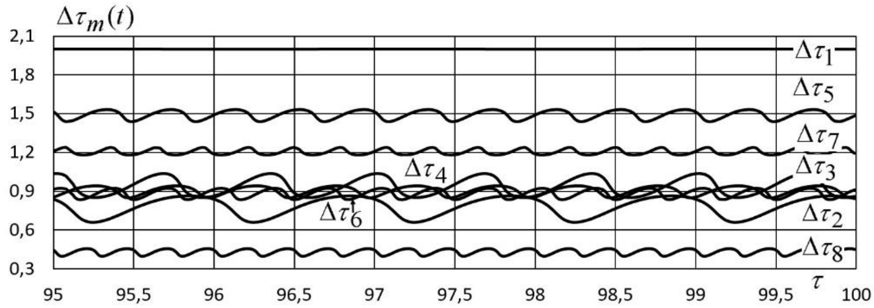

Fig. 5. Transport delay value (steady-state) $\Delta\tau_{\mathrm{m}}(\tau)$ for the m–th section

4 Linear regression conveyor model

To predict the value of the output flows θ_{17}, θ_{18} for the sections m=7,8 of the transport system (Fig. 2), let us research for the linear regression equation in the form

$$\theta_{17_i} = a_0 + \sum_k a_{\gamma k}\gamma_{m\,i} + \sum_k a_{gk} g_{k\,i} + \varepsilon_{7\,i} = \theta_{17_{0\,i}} + \varepsilon_{7\,i}, \tag{11}$$

$$\theta_{18_i} = b_0 + \sum_k b_{\gamma k}\gamma_{k\,i} + \sum_m b_{gk} g_{k\,i} + \varepsilon_{8\,i} = \theta_{18_{0\,i}} + \varepsilon_{8\,i}, \tag{12}$$

where $\varepsilon_{7\,i} = \theta_{17_i} - \theta_{17_{0\,i}}$, $\varepsilon_{8\,i} = \theta_{18_i} - \theta_{18_{0\,i}}$ are prediction errors; $i = 1..N$, N is the number of rows in the sample.

The frequency diagrams for the value of the output flow $\theta_{17}(\tau,1)$, $\theta_{18}(\tau,1)$ of the sections m=7,8 are presented in Fig. 6, Fig. 7.

The coefficients a_k, b_k of the linear regression (11), (12) are determined from the condition for the minimum value of the mean square error (MSE)

$$MSE_m = \sigma_m^2 = \frac{1}{N}\sum_i^N \varepsilon_{m\,i}{}^2 \to \min, \quad \sum_i^N \varepsilon_{m\,i} = 0. \tag{13}$$

The number of intervals selected in accordance with the Sturges' rule [26]

$$r = 3.3 \lg N + 1 = 14 \; . \qquad (14)$$

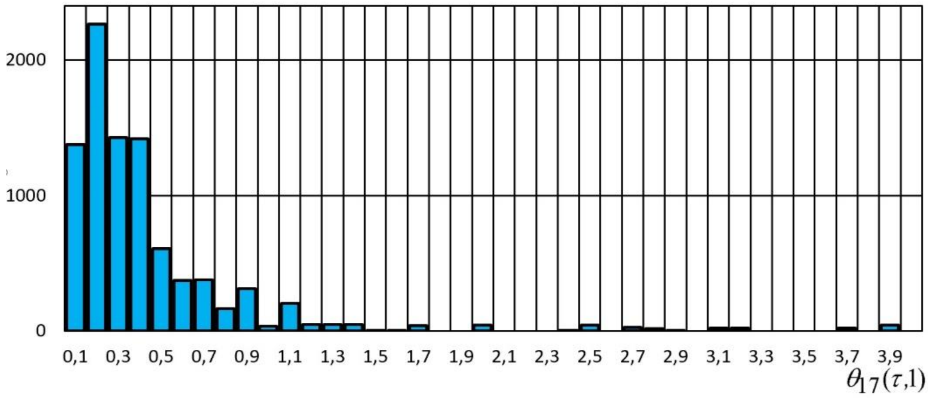

Fig. 6. The frequency diagram for output flow values $\theta_{17}(\tau,1)$

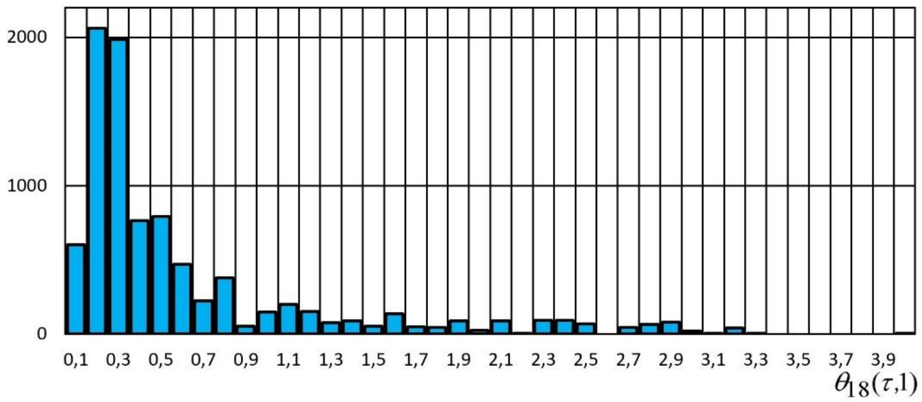

Fig. 7. The frequency diagram for output flow values $\theta_{18}(\tau,1)$

5 Analysis of the results

The linear regression model for predicting the values of the output flow $\theta_{17}(\tau,1)$, $\theta_{18}(\tau,1)$ taking into account the optimality condition (13), takes the form

$$\theta_{17_0} = 0.2246 - 0{,}4670 \;\; \gamma_1 - 0{,}0773 \;\; g_1 - 1{,}2839 \;\; \gamma_2 - 0{,}7349 \;\; g_2 - \qquad (15)$$

$$+ 0{,}4291 \;\; \gamma_4 - 0{,}082 \;\; g_4 + 1{,}2396 \;\; \gamma_5 + 0{,}4853 \;\; g_5 ,$$

$$\theta_{18_0} = 2.3045 + 0{,}4876 \;\; \gamma_1 - 0{,}2674 \;\; g_1 - 0{,}6290 \;\; \gamma_2 - 0{,}9600 \;\; g_2 - \qquad (16)$$

$$-0{,}4127\ \gamma_4 - 0{,}0233\ g_4 - 0{,}4074\ \gamma_5 - 0{,}6636\ g_5,$$

The mean square error for the model (15), (16) is MSE_7 =0,223. The null hypothesis H_0 that the error ε_7 has a normal distribution law is rejected (the significance level $\alpha = 0.05$, $p_{value} << \alpha$). The value of the output flow $\theta_{17}(\tau,1)$, $\theta_{18}(\tau,1)$ does not depend on the input parameters of the transport system linearly. The frequency diagram for the error ε_7 is shown in Fig. 8. The expressed peak values of the function characterize the features of the process under consideration, that provides resonant values of the flow parameters. To analyze the nonlinear dependence, let us use the transformation $Z_m = \ln(\theta_{1\mathrm{m}})$ for the model output parameters (11), (12)

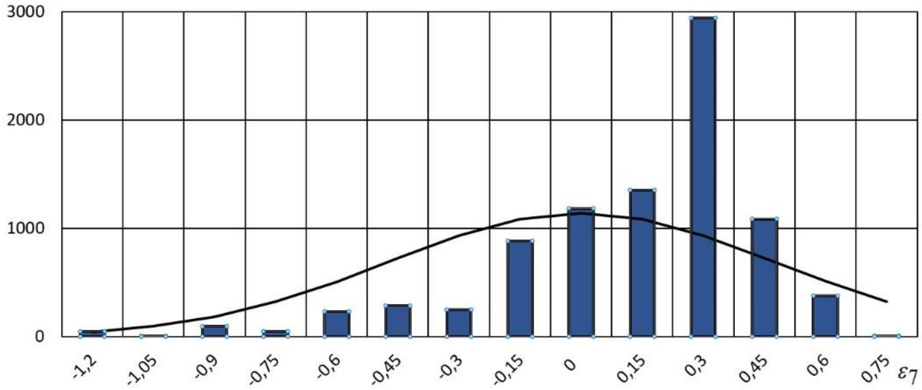

Fig. 8. The frequency diagram for the error ε_7

The transformation $Z_m = \ln(\theta_{1\mathrm{m}})$ leads to a linear model of the form

$$Z_{7i} = \ln\left(\theta_{17_i}\right) = a_0 + \sum_k a_{\gamma k} \gamma_{m\,i} + \sum_k a_{gk}\, g_{k\,i} + \varepsilon_{7\ln i} = \ln\left(\theta_{17_{0i}}\right) + \varepsilon_{7\ln i}, \quad (17)$$

$$Z_{8i} = \ln\left(\theta_{18_i}\right) = b_0 + \sum_k b_{\gamma k} \gamma_{k\,i} + \sum_m b_{gk}\, g_{k\,i} + \varepsilon_{8\ln i} = \ln\left(\theta_{18_{0i}}\right) + \varepsilon_{8\ln i}. \quad (18)$$

The coefficients of the transforming model determine from the condition for optimality (13)

$$Z_{70} = -1.591 - 1.1907\ \gamma_1 - 1.4431\ g_1 - 1.5514\ \gamma_2 - 1.3523\ g_2 - \quad (19)$$

$$+0.9471\ \gamma_4 - 0.1986\ g_4 + 2.8164\ \gamma_5 + 1.2725\ g_5,$$

$$Z_{80} = -1.1385 + 1{,}3829\ \gamma_1 + 0{,}1628\ g_1 - 0.7624\ \gamma_2 - 0.4666\ g_2 - \tag{20}$$

$$-0.9676\ \gamma_4 - 0{,}0168\ g_4 + 1{,}2558\ \gamma_5 + 1{,}1076\ g_5,$$

The mean square error for the model (19), (20) amounts $MSE_{7\ln} = 0.8467$. The mean square error for the model, taking into account the inverse transformation $\theta_{17} = \exp(Z_7)$, is the value MSE_7 =0,259. This value is higher than the value of the model (15),(16). The null hypothesis H_0 that the error $\varepsilon_{7\ln}$ has a normal distribution law is rejected (the significance level $\alpha = 0.05$, $p_{value} << \alpha$, $\chi^2 / \chi^2_{cr} \sim 50$). The value Z_{70}, Z_{80} of the output flow $\theta_{17}(\tau,1)$ and $\theta_{18}(\tau,1)$ does not depend on the input parameters of the transport system linearly. The frequency diagram for the error $\varepsilon_{7\ln}$ is given in Fig.9. The frequency diagram shows that the density function of the error $\varepsilon_{7\ln}$ is more qualitatively approaching the normal distribution law. However, the presence of resonance values for the output parameters still leads to a significant asymmetry of the distribution density.

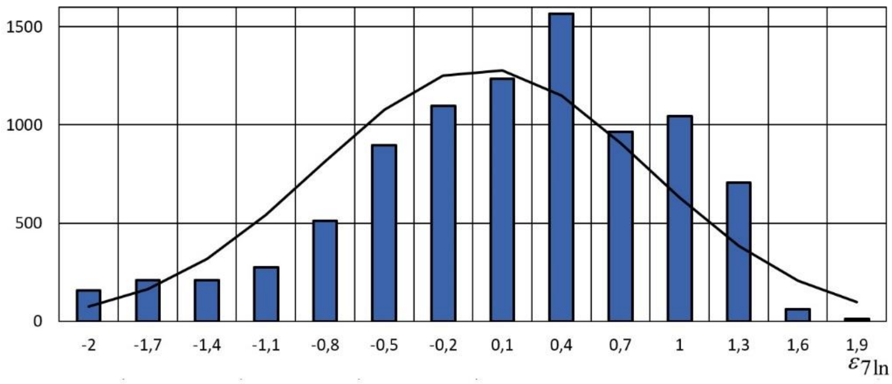

Fig. 9. The frequency diagram for the error $\varepsilon_{7(\ln+1)}$

Figure 10 shows the frequency diagram $\varepsilon_{7(\ln+1)}$ for the transformation $Z_7 = \ln(\theta_{17} + 1)$:

$$Z_{7i} = a_0 + \sum_k a_{\gamma k} \gamma_{m\,i} + \sum_k a_{gk} g_{k\,i} + \varepsilon_{7l(n+1)i} = \ln\left(\theta_{17_{0\,i}} + 1\right) + \varepsilon_{7(\ln+1)i}. \tag{21}$$

The mean square error for the model (21) is. $MSE_{7(\ln+1)} = 0.054$. The mean square error for the model, taking into account the inverse transformation, $\theta_{17} = \exp(Z_7) - 1$ is MSE_7 =0,222. The null hypothesis H_0 that the error $\varepsilon_{7(\ln+1)}$ has the normal distribution law was rejected (the significance level is $\alpha = 0.05$, $p_{value} << \alpha$, $\chi^2 / \chi^2_{cr} \sim 25$). As in previous cases, the value Z_{70} and Z_{80} for the output flow $\theta_{17}(\tau,1)$ and $\theta_{18}(\tau,1)$ does not depend on the input parameters of the transport system linearly.The prediction results of the output flow $\theta_{17}(\tau,1)$ are presented in Fig. 11. The time interval $\tau \in [95;100]$ over which the system is insensitive to the initial conditions is considered. The exact value of the output flow $\theta_{17}(\tau,1)$ has resonance peaks characteristic of the system under consideration. As in previous cases, the value MSE_7 for each model coincides practically. The max fluctuations amplitude of the value output flow has the model (the model is indicated by number 2 in Fig. 11).

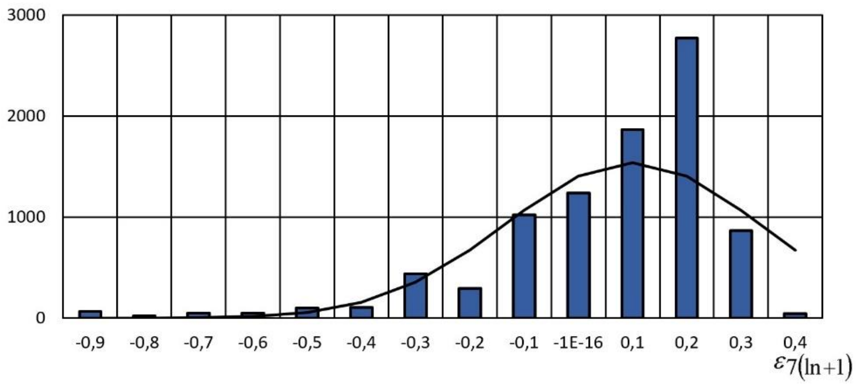

Fig. 10. The frequency diagram for the error $\varepsilon_{7(\ln+1)}$

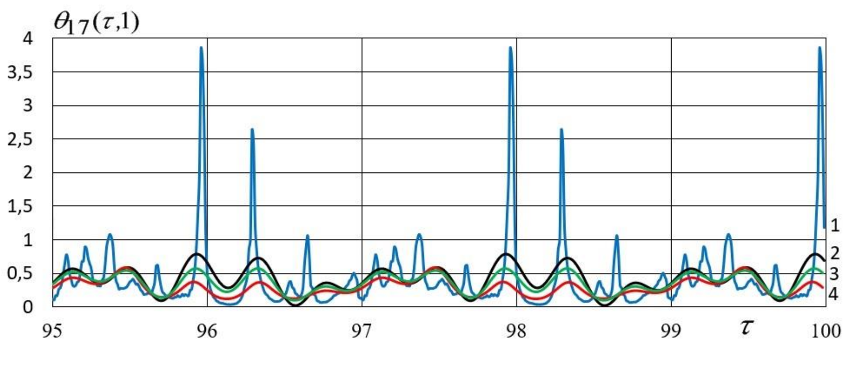

Fig. 11. The predicted values for the output flow $\theta_{17}(\tau,1)$

The type of function for predicting each of the models coincides qualitatively. Themodel (15) has a predicted value higher than other models. Lower predicted values correspond to model (19) (the model is indicated by number 4 in Fig. 11).

The predicted values of the model (21) (the model is indicated by number 3 in Fig. 11) occupy intermediate values between model (15) and (19). It should also be noted that the predicted value for each model is represented by a periodic function with a period of the same value for each model. Also, a characteristic property for the developed regression models is the fact that the local maxima of these models have the same value τ .

Conclusion

The main result of the research is to determine the perspectives for using linear regression models and their transformation options for describing a multi-section transport system.

A characteristic feature of the functioning of a multi-section transport system is the presence of resonant peak values for the flow parameters of the transport system. This is due to the periodic nature of the magnitude of the incoming material flow into the transport system and the periodic nature of the regulation of the speed of the belt with the subsequent superposition of the transport flows on each other.

The analysis indicates the absence of a linear relationship between the value of the parameters of the input sections $\gamma_m(\tau)$ и $g_m(\tau)$ and the value of the parameters θ_{17}, θ_{18} output sections of the transport system. The presented regression models give a qualitative aggregated idea of the magnitude of the output flow θ_{17},, but do not allow predicting the time moments of the functioning of the transport system with overloads and peak values due to superposition flows from individual sections of the transport system. Using linear regression models to predict the material output in such systems is inefficient. It is required to build strongly non-linear regression models that allow one to evaluate the effects associated with the superposition of material flows from different sections.

No less important result, that presents in the paper, is that transport delay is quasi-stationary value, and can be excluded from the regressor set of the model.

The results obtained in this article determined the prospects for further research, among which should be highlighted:a) determination of the functioning modes of individual sections of the transport system, in which resonant values of the flow parameters arise; b) development of nonlinear regression models for predicting the state of the transport system parameters and designing optimal control systems for these parameters.

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